Overview of NOVAS Version F3.0

George Kaplan
U.S. Naval Observatory

Version F3.0 of the Naval Observatory Vector Astrometry Subroutines (NOVAS) implements the resolutions on astronomical reference systems and Earth rotation models passed at the IAU General Assemblies in 1997, 2000, and 2006. This version of NOVAS (2006) also improves the accuracy of its star and planet position calculations (apparent places) by including several small effects not previously implemented in the code. A number of new convenience functions have also been added. The implications of the recent IAU resolutions can be found in USNO Circular 179 (2005), *The IAU Resolutions on Astronomical Reference Systems, Time Scales, and Earth Rotation Models: Explanation and Implementation*, and contains much more information on topics only briefly touched on below.

A detailed list of the changes in NOVAS from the previous version (F2.0 of 1998) is given in the Appendix. The following paragraphs are meant to provide some perspective for people who are already familiar with NOVAS. To the greatest extent possible, the calling sequences for the highest-level (and most used) functions from the previous versions of NOVAS have been preserved — but there are a few important exceptions. There are many new calls.

Important Changes in Existing Calls

Probably the most important change to existing NOVAS calls is the change of proper motion and parallax units in the calls to APSTAR, VPSTAR, and ASSTAR, CATRAN, and GETHIP, all of which deal with star positions. The units have been changed as follows:

> proper motion in right ascension: from seconds of RA per century to milliarcseconds per year
> proper motion in declination: from arcseconds per century to milliarcseconds per year
> parallax: from arcseconds to milliarcseconds

These changes have been made to conform to the units used in most modern star catalogs (e.g., Hipparcos, Tycho-2, or the FK6), which in turn follow from the observational techniques now used in the construction of such catalogs. Obviously, star data previously used with NOVAS must either be replaced or transformed. The transformation equations from "old" to "new" units are as follows:

```
PMRNEW = PMROLD * 150.D0 * DCOS ( DEC0 * DEGRAD )  ; proper motion in RA
PMDNEW = PMDOLD * 10.D0                            ; proper motion in dec
PAXNEW = PAXOLD * 1000.D0                          ; parallax
```

where `DEC0` is the catalog declination (J2000.0 or ICRS) of the star in degrees and `DEGRAD` is the degrees-to-radians conversion factor (0.01745329…).

The other major change to a high-level subroutine is that PNSW has been renamed to TERCEL (it carries out the terrestrial-to-celestial transformation), with a change to the time argument. All other changes to existing NOVAS calls involve lower-level routines not frequently invoked by most users; these are detailed in the Appendix.

PLACE: A New General-Purpose "Place" Subroutine

All computational code to compute apparent, topocentric, virtual, astrometric, etc., places of stars or planets has now been consolidated into a single new subroutine call PLACE. The familiar calls to APSTAR, APPLAN, TPSTAR, etc., still work as before but are now just "front-ends" to PLACE. This has eliminated much duplicate code and also provides more flexibility and possible future additions (such as binary star orbits or nonlinear terms in proper motion). PLACE can also provide star or planet positions within the "intermediate" coordinate system that is part of the new paradigm for Earth rotation calculations (see below). PLACE provides its output position both in spherical coordinates (right ascension, declination, and, for solar system bodies, geometric distance) and as a unit vector. PLACE also provides radial velocity. PLACE accepts the specification of solar system bodies by name, e.g., 'MARS', 'SATURN', or 'SUN', thus increasing the readability of code. You may want to consider changing your calls to APSTAR, APPLAN, etc., to the equivalent calls to PLACE.

New Reference Systems

In 2000, the IAU defined a system of space-time coordinates for (1) the solar system, and (2) the Earth, within the framework of General Relativity, by specifying the form of the metric tensors for each and the 4-dimensional space-time transformation between them. The former is called the Barycentric Celestial Reference System (BCRS) and the latter is called the Geocentric Celestial Reference System (GCRS). The BCRS is the system appropriate for the basic ephemerides of solar system objects and astrometric reference data on galactic and extragalactic objects. The GCRS is the system appropriate for describing the rotation of the Earth, the orbits of Earth satellites, and geodetic quantities such as instrument locations and baselines. The analysis of precise observations inevitably involves quantities expressed in both systems and the transformations between them. Subroutines in NOVAS may work with BCRS vectors, GCRS vectors, or, with appropriate conversions, both.

If we specify the orientation of the BCRS axes in space, the orientation of the GCRS axes then follows from the relativistic transformation between the two systems. The orientation of the BCRS is given by what is called the International Celestial Reference System (ICRS). The ICRS is a triad of coordinate axes with origin at the solar system barycenter and with axis directions effectively defined by the adopted coordinates of about 600 extragalactic radio sources observed by VLBI (see Section H of *The Astronomical Almanac*). These radio sources (quasars and active galactic nuclei) are assumed to have no observable intrinsic angular motions. Thus, the ICRS is a "space-fixed" system (more precisely, a kinematically non-rotating system) without an associated epoch. However, the ICRS was set up to closely match the conventional dynamical system defined by the Earth's mean equator and equinox of J2000.0; the alignment difference is at the 0.02 arcsecond level, negligible for many applications. Reference data for positional astronomy, such as the data in astrometric star catalogs (e.g., Hipparcos) or barycentric planetary ephemerides (e.g., JPL's DE405) are now specified within the ICRS; more precisely, they are specified within the BCRS, with respect to the ICRS axes. The abbreviations BCRS and ICRS are often used interchangeably; and loosely speaking, the GCRS can be thought of as the "geocentric ICRS".

NOVAS now assumes that input reference data, such as catalog star positions and proper motions, and the basic solar system ephemerides, are provided in the ICRS (that is, within the BCRS as aligned to the ICRS axes), *or at least are consistent with it to within the data's inherent accuracy*. The latter case will probably apply to most FK5-compatible data specified with respect to the mean equator and equinox of J2000.0 (the "J2000.0 system"). The distinction between the ICRS and the J2000.0 system becomes important only when an accuracy of 0.02 arcsecond or better is important. Nevertheless, because NOVAS is designed for the highest accuracy applications, you will now see the ICRS mentioned as the reference system of choice for many input arguments to NOVAS subroutines.

Because the ICRS axes are not precisely aligned to those of the J2000.0 system, there is a new subroutine called FRAME to transform vectors between the two systems. This transformation is a very small fixed rotation. FRAME is used for both barycentric vectors (BCRS/ICRS to or from the barycentric J2000.0 system) and geocentric vectors (GCRS to or from the geocentric J2000.0 system). FRAME is called many times, in both directions, within the NOVAS code. That is because precession (and nutation) can properly be applied only to vectors in a real equatorial system; vectors in the GCRS (geocentric ICRS) must be transformed, via FRAME, to the J2000.0 system before PRECES is used. If your code only interacts with the highest level NOVAS subroutines, all this is transparent to you. However, if you use PRECES within your own code, you should precede it by a call to FRAME (with the middle argument K>0) if your input vector is expressed in the GCRS, that is, if it is derived from an input source based on the ICRS.

New Features

Subroutines have been added to NOVAS that provide new functionality and convenience:

PLACE: A new general-purpose apparent place subroutine (see paragraph above).

IDSS: An integer function that returns a solar system body's identification number (which is used in various NOVAS subroutine calls), given the body's name as a character string. For example, `IDSS('MARS')` usually equals 4. Because IDSS is a function, it can be referred to within calls to other NOVAS subroutines, e.g.,

```
     CALL APPLAN ( TTJD, IDSS('JUPITER'), IDSS('EARTH'), RAJUP, DECJUP, DISJUP )
```

(If you supply your own version of subroutine SOLSYS, you must also now supply a corresponding version of IDSS.)

GETVEC: A subroutine that returns the last NOVAS-computed celestial position (apparent or astrometric place, etc.) as a unit vector. The vector is expressed in the same reference system as the previously supplied spherical coordinates.

EQECL: Converts right ascension and declination to ecliptic longitude and latitude. Also, EQEC and ECEQ convert vectors from an equatorial to an ecliptic basis and vice versa, respectively.

EQGAL: Converts ICRS right ascension and declination to galactic longitude and latitude.

GCRSEQ: Converts GCRS (geocentric ICRS) right ascension and declination to one of the equatorial systems of date.

ASTCON: Supplies the value of an astronomical constant, given its name as a character string. The values of all fundamental astronomical constants used by NOVAS are stored within this subroutine and nowhere else. The names of the constants available and the units used for each are listed in the subroutine's preamble. For example, `CALL ASTCON ('ERAD',1.D0,RADIUS)` returns, in argument `RADIUS`, the value of the equatorial radius of the Earth in meters.

New Models for Precession and Nutation

It has been known for over a decade that the old standard models for the precession and nutation of the Earth's rotation axis have been in need of revision. The value of the angular rate of precession in longitude adopted by the IAU in 1976 — and incorporated into the widely used precession formulation by Lieske and collaborators — is too large by about 0.3 arcsecond per century (3 mas/yr). The amplitudes of a number of the largest nutation components specified in the 1980 IAU Theory of Nutation are also known to be in error by several milliarcseconds. Both the precession and nutation errors are significant relative to current observational capabilities.

Thus, the resolutions passed by the IAU in 2000 mandated an improvement to the precession and nutation formulations. The 2006 version of NOVAS incorporates the models adopted in response to these resolutions. The precession model is the P03 solution of Capitaine, et al. (2003) A&A 412, 567, as recommended by the IAU Working Group on Precession and the Ecliptic, whose final report is Hilton et al. (2006) Celest. Mech. Dyn. Astr. 94, 351. The P03 precession model was formally adopted by the IAU in 2006. The nutation model, sometimes referred to as "MHB" from the initials of the three authors' last names, is from Mathews, et al. (2002) J. Geophys. Res. 107, B4, ETG 3. Despite the new models, from a programming point of view, the subroutines that directly involve precession and nutation — PRECES, NUTATE, ETILT, NOD, and SIDTIM — work the same as before, but with slightly different results. It should be noted that the new nutation model has more than ten times the number of trigonometric terms than the previous model. Since evaluation of nutation has always been the most computationally intensive task in NOVAS, you may notice an increase in execution time for some NOVAS applications (more on this below).

A New Model for the Rotation of the Earth about its Axis

IAU resolutions passed in 2000 also dealt in a very fundamental way with how we describe the Earth's spin *around* its axis. The conventional treatment is based on the equinox and sidereal time; Greenwich (or local) sidereal time is just the Greenwich (or local) hour angle of the equinox of date. However, the equinox is constantly moving due to precession, so that sidereal time combines two angular motions, the Earth's rotation and the precession of its axis. (In the case of apparent sidereal time, nutation is also mixed in.) One rotation of the Earth is about 0.008 second longer than one mean sidereal day.

For about two decades, people who routinely deal with the most precise measurements of the Earth's rotation have been advocating for a change in the way it is described, and their ideas were introduced in resolutions passed by the IAU in 2000. In this new paradigm, the reference point on the moving celestial equator for the description of Earth rotation is called the Celestial Intermediate Origin (CIO). Unlike the equinox, this point has no motion along the equator at all; as the orientation of the equator changes in space due to precession and nutation, the CIO remains on the equator but its instantaneous motion is always at right angles to it. Thus, loosely speaking, two transits of the CIO across a terrestrial meridian define one rotation of the Earth. The CIO is a point on the celestial equator near RA=0, and there is a corresponding point on the terrestrial equator near longitude=0 called the Terrestrial Intermediate Origin (TIO). For all astronomical purposes, the TIO can be considered a point fixed on the surface of the Earth at the rotational equator and at longitude zero.[1] In the new

[1] The CIO and TIO are technically examples of *non-rotating origins*, and neither is fixed within its respective coordinate system. However, the slow drift of the TIO, due to polar motion, with respect to

paradigm, the rotation of the Earth is specified by the angle (in the instantaneous equatorial plane) between the TIO and the CIO, which is a linear function of universal time (UT1). This angle is called the Earth Rotation Angle (ERA) and is designated by θ.

How are hour angles of celestial objects computed in the old and new paradigms? Assume that we are considering “Greenwich” hour angles, that is, hour angles measured from the meridian of longitude zero, and without polar motion. In the equinox-based scheme, we compute the topocentric apparent place of the object of interest with respect to the true equator and equinox of date. Then we compute apparent sidereal time and subtract the object’s apparent right ascension to form the hour angle. In the CIO-based scheme, we compute the object’s topocentric apparent place with respect to the true equator and CIO of date. To form the hour angle, we compute the Earth rotation angle and subtract the angle along the true equator measured eastward from the CIO to the object (this coordinate is called the *intermediate right ascension*). Since hour angle is an observable quantity, the two results should be identical. You might wonder, then, what the advantage of the new system is. In the equinox-based scheme, precession and nutation appear in both the apparent place of the star and sidereal time. In the CIO-based scheme, they appear only in the apparent place of the star. The CIO-based method also does not depend on the equinox, and is thus independent of any model of the Earth’s orbital motion.

The following table summarizes the two equivalent procedures for hour angle and the NOVAS subroutines that would be used for each, assuming that polar motion is neglected. The procedures outlined here provide the Greenwich hour angle of a star.

	Equinox-Based Method	**CIO-Based Method**
Use subroutine	APSTAR followed by TPSTAR — or — PLACE with OBJECT=′STAR′, LOCATN=1, and ICOORD=1	PLACE with OBJECT=′STAR′, LOCATN=1, and ICOORD=2
… to obtain	RA and DEC, the topocentric apparent right ascension and declination of the star with respect to the equator and equinox of date (in hours and degrees, respectively)	RA and DEC, the topocentric apparent right ascension and declination of the star with respect to the equator and CIO of date (in in hours and degrees, respectively)
Then use subroutine	SIDTIM with K=1	EROT
… to obtain	GST, Greenwich apparent sidereal time (in hours)	THETA, the Earth rotation angle, θ (in degrees)
Compute Greenwich hour angle	GHA = GST – RA, (in hours)	GHA = THETA / 15.D0 – RA, (in hours)

The computed GHA may have to be reduced to the range -12^h to $+12^h$. Subroutines APSTAR and PLACE require time arguments in the TT time scale, while TPSTAR, SIDTIM, and EROT require time arguments in the UT1 time scale. The two procedures should yield the same value of GHA to within several microarcseconds and identical values for DEC.

---

standard geodetic coordinates (the International Terrestrial Reference System, or, effectively, WGS84) amounts to only 1.5 millimeters per century and is completely negligible for astronomical purposes.

Two high-level NOVAS subroutines that involve Earth rotation, SIDTIM and TERCEL (the latter replaces the old PNSW) can actually perform their internal calculations using either the equinox-based paradigm or the CIO-based paradigm. (Note: ZDAZ is also affected because it calls TERCEL.) The method used is selected by a prior call to either EQINOX or CIOTIO (without arguments), which remains in effect until changed. Since there is no external difference in how SIDTIM or TERCEL are used, and the two computational paradigms yield answers that are consistent within a few micro-arcseconds over many centuries, there is seldom a practical basis for a choice. However, the equinox method must be used for dates before 1700 or after 2300, and is much more efficient if mean sidereal time is to be computed. The equinox-based paradigm is the default, that is, it is used unless CIOTIO has been called. That will, of course, be the case for any existing programs that are not updated to make this choice explicit.

Another choice is now available that has a more practical effect: Earth rotation calculations can be performed in either high- or low-accuracy mode. A call to either HIACC or LOACC (without arguments) sets the accuracy, which remains in effect until changed. High-accuracy mode is the default, with the various models evaluated at the few-microarcsecond level. For nutation, for example, this means that a 1365-term trigonometric series is evaluated for each unique date. Neither the models nor current observations are accurate at this level, however, so much of the increased computational burden is unproductive. A call to LOACC sets the Earth rotation computations (and *only* those computations) in NOVAS to an accuracy of 0.1 milliarcsecond. The computation time for these calculations is thereby reduced by about 2/3.

Finally, another of the new Earth-rotation-related subroutines is worth mentioning. For a given TDB date, CIORA provides the right ascension of the CIO with respect to the true equator and equinox of date. With a sign reversal, this quantity is the *equation of the origins*, the direction of the true equinox measured in the equator eastward (+) from the CIO. The equinox and CIO can be considered different right ascension origins on the instantaneous equator, and as such they define separate equatorial systems for the equinox-based and CIO-based paradigms. CIORA therefore provides the angular difference between the origins of these two systems.

Some Terminology

Not surprisingly, the IAU resolutions related to Earth rotation have required some new terminology, and an IAU Working Group on Nomenclature for Fundamental Astronomy was established for the 2003–2006 triennium to sort it all out. The most commonly used terms and abbreviations now appear in comment statements in some of the new NOVAS subroutines, including the preambles where the input and output arguments are described. A brief summary of these terms is therefore in order here. The Celestial Intermediate Origin (CIO) and Terrestrial Intermediate Origin (TIO) have already been described; these concepts were established in a 2000 IAU resolution although the final terminology was not formally adopted until 2006. A term specifically introduced in a 2000 resolution is the Celestial Intermediate Pole (CIP), which is the celestial pole defined by the new precession and nutation models. The true equator of date is a plane orthogonal to the CIP. The coordinate system defined by the true equator of date and the CIO is referred to as the Celestial Intermediate Reference System; the word “intermediate” is used because this system is, in a sense, midway between the rapidly rotating terrestrial latitude-longitude system and the completely non-rotating GCRS (geocentric ICRS). The spherical coordinates in this system are called *intermediate right ascension* and *intermediate declination*; intermediate right ascension is the azimuthal coordinate measured in the instantaneous equatorial plane eastward from the CIO, and intermediate declination is the same as true or instantaneous declination.

How NOVAS Implements the CIO-Based Paradigm

The NOVAS implementation of the CIO-based Earth rotation paradigm for a given date is based on the construction of the Celestial Intermediate Reference System for that date, using vectors toward the Celestial Intermediate Pole (CIP) and the Celestial Intermediate Origin (CIO). These two directions define, respectively, the z-axis and x-axis of the celestial intermediate system. The direction toward the CIP in the GCRS (geocentric ICRS) can be computed by passing the vector (0,0,1) through subroutines NUTATE, PRECES, and FRAME. Given the direction of the CIP, the other piece of required information is the location of the CIO for the same date, which is provided by CIOLOC. The basis vectors of the intermediate system, with respect to the GCRS, are computed by CIOBAS. Having these basis vectors available allows NOVAS to easily transform any vector in the GCRS to the intermediate system. The only other quantity used in the CIO-based paradigm is the Earth rotation angle, which is trivial to compute and provided by EROT.

The only tricky part of this process is obtaining the location of the CIO, which is a unique quantity derived from an integration. CIOLOC obtains the location of the CIO for a given date in one of two ways, and an output argument, K, indicates which way was used. If an external file of CIO right ascension values is available (nominally called 'CIO_RA.TXT' and located in the current directory) then CIOLOC will provide the GCRS right ascension of the CIO, and will set K to 1. If this file is not available, then CIOLOC will provide the true right ascension of the CIO (the arc on the instantaneous equator from the equinox to the CIO), obtained from a series expansion, and will set K to 2. CIOBAS can work with either coordinate of the CIO. The two methods are equivalent within several microarcseconds over six centuries centered on the year 2000.

To do the hard work, CIOLOC calls either CIORD (for K=1) or EQXRA (for K=2). CIOLOC always initially calls CIORD to see if the external file of CIO right ascensions is present. If it is, CIORD reads and interpolates the file, which is the output from a numerical integration covering years 1700 to 2300 and directly provides the right ascension of the CIO in the GCRS. You can specify the path/name of this file, its type (sequential or direct-access), and the logical unit number on which it is to be read, by using a call to CIOFIL, which must precede any CIO-based computation. If you don't call CIOFIL, CIORD will look for a formatted sequential file named CIO_RA.TXT in the current directory (folder) and, if present, will read it on logical unit 24. A copy of CIO_RA.TXT is available in the NOVAS directory (7.5 Mbytes), along with a utility program called CIO_file.f to convert it to a binary direct-access file (2.9 Mbytes) if desired.

If the file is not present, then CIOLOC calls EQXRA to evaluate the equation of the origins from a closed-form expression that includes the evaluation of nutation in longitude, a lengthy series of trigonometric terms. The result locates the CIO with respect to the equinox on the instantaneous equator.

Existing NOVAS programs, unless specifically modified, will not use the CIO-based paradigm for Earth rotation; neither CIOLOC or CIOBAS will be called and the external file of CIO right ascensions is superfluous. However, in the equinox-based paradigm, both EROT and EQXRA are used in the computation of sidereal time. Apparent sidereal time is comprised of the Earth Rotation Angle, θ, plus the accumulated precession and nutation in right ascension, which is -1 times the equation of the origins. Therefore, SIDTIM now computes apparent sidereal time simply by subtracting the result of EQXRA from that of EROT.

Appendix

Changes to NOVAS – From Version F2.0 (1998) to Version F3.0 (2006)

New Subroutines

NU2000A – from IERS (Wallace), evaluates IAU 2000A nutation series (nutation only).

NU2000K – modification of NU2000A, evaluates truncated version of full IAU 2000 A. More accurate than IAU 2000 B series. Also uses a consistent set of expressions for the fundamental arguments, those of Simon et al. (1994). Accuracy: about 0.1 mas for $\Delta\psi$, about 0.04 mas for $\Delta\varepsilon$ and $\Delta\psi \sin \varepsilon$.

EECT2000 – from IERS (Wallace), evaluates 34-term series for "complementary terms" in equation of the equinoxes.

EROT – evaluates the Earth rotation angle θ.

FRAME – sets up frame tie matrix and transforms vector from dynamical mean J2000.0 system to ICRS, or vice versa. FRAME implements a first-order matrix with second-order corrections to the diagonal elements, patterned after what is given in the Hilton and Hohenkerk (2004) A&A paper. Given the smallness of the angles involved and their uncertainties, this is quite adequate.

PLACE – New, general-purpose subroutine for computing apparent, topocentric, virtual, astrometric, etc., places of stars and planets. All substantive code for performing these calculations has been moved from APSTAR, TPSTAR, APPLAN, etc., into PLACE. In the call to PLACE, the object requested is specified by name, using a character argument, e.g., 'SUN', 'MOON', 'JUPITER', 'STAR', etc. The type of place requested is specified by two input codes, one indicating the location of the observer and the other indicating the coordinate system of the output positions. APSTAR, TPSTAR, APPLAN, etc., now are just "front-ends" to PLACE.

SETVEC – stores the last-computed celestial position vector.

GETVEC – allows the user to retrieve the last-computed celestial position as a unit vector.

IDSS – returns the planet number of a specified solar system body, to be used in calls to SOLSYS, APSTAR, APPLAN, etc. Actually a FUNCTION. The solar system body is specified by its name (all upper case letters) in the character variable that is the single input argument. For example, IDSS('EARTH') = 3 (usually). A version of IDSS must now be packaged with each version of SOLSYS.

ASTCON – provides values of astronomical constants.

SETDT – allows user specification of ΔT (=TT–UT1) value in seconds. The ΔT value set here is used both in SIDTIM and TERCEL and, in certain circumstances, in PLACE.

GETDT – retrieves ΔT value (in days) previously specified via SETDT (in seconds).

GCRSEQ – transforms GCRS RA & Dec to RA & Dec on mean or true equator of date. For true equator of date, either the true equinox or the CIO can be specified as the origin of right ascension.

EQECL – converts equatorial RA & Dec to ecliptic longitude and latitude.

EQEC – converts an equatorial position vector to an ecliptic position vector.

ECEQ – converts an ecliptic position vector to an equatorial position vector.

EQGAL – converts ICRS RA & Dec to galactic longitude and latitude.

DLIGHT – evaluates the difference in light-time to a star between the solar system barycenter and the Earth.

GRVDEF – replacement for SUNFLD that supervises the evaluation of gravitational deflection of light due to the Sun, Jupiter, and other solar system bodies. Calls new subroutine GRVD to do the deflection calculation for each body.

GEOPOS – called from PLACE to compute the geocentric position and velocity vectors of an observer on or above the surface of the Earth.

LITTIM – called from PLACE to antedate the position of a solar system body for light-time.

LIMANG – evaluates where an observed object is with respect to the Earth's limb (horizon), given the geocentric position vectors of the observer and the object. PLACE calls LIMANG for the topocentric cases in deciding whether to include the gravitational deflection of light due to the Earth itself.

CIORA – returns the value of the true right ascension of the CIO for a given TDB Julian date.

CIOLOC – returns the right ascension of the CIO at a given TDB Julian date, either with respect to the GCRS or the true equator and equinox of date.

CIORD – called from CIOLOC, reads and returns a set of values of the GCRS right ascension of the CIO, near a given TDB Julian date, from an external file (either formatted sequential or binary direct-access).

CIOFIL – allows the specification of the external file of CIO right ascensions that CIORD reads.

CIOBAS – returns orthonormal basis vectors for Celestial Intermediate Reference System with respect to the GCRS. Requires previous call to CIOLOC.

EQXRA – returns the value of the Equation of the Origins, i.e., the right ascension of the equinox in the Celestial Intermediate Reference System, from an analytical expression. The Equation of the Origins is the arc on the true equator of date from the CIO to the equinox, measured positively to the east.

RADVL – called from PLACE to compute the radial velocity of observed object with respect to the observer.

SETMOD – sets method/accuracy mode for Earth rotation calculations.

GETMOD – retrieves method/accuracy mode for Earth rotation calculations.

EQINOX – specifies that equinox-based method is to be used for Earth rotation calculations.

CIOTIO – specifies that the CIO-based method is to be used for Earth rotation calculations.

HIACC – specifies that high-accuracy (~1 μas) algorithms are to be used for Earth rotation calculations.

LOACC – specifies that low-accuracy (~0.1 mas) algorithms are to be used for Earth rotation calculations.

RESUME – reverts to method/accuracy mode used prior to latest change (by one of the above subroutines).

<u>Changes to Existing (NOVAS Version F2.0) Calling Sequences</u>

APSTAR, VPSTAR, ASSTAR, CATRAN, GETHIP, VECTRS – proper motion units (in both RA and Dec) changed to milliarcseconds/year (pm in RA includes cos δ factor), parallax units changed to milliarcseconds.

TPSTAR, TPPLAN, LPSTAR, LPPLAN – the user's option to specify the input time argument as apparent sidereal time in hours is now discouraged; specifying the corresponding UT1 Julian date is now recommended. Sidereal time input is still supported but might not be in future NOVAS releases.

PRECES, CATRAN – one of the input epochs must now be 2451545.0 (J2000.0). Can no longer do two arbitrary epochs (the new precession expressions are not as flexible as Newcomb's or Lieske's).

CATRAN – has two new transformation options: IT=4 rotates data from the dynamical equator and equinox of J2000.0 to the ICRS and IT=5 does the opposite rotation.

WOBBLE – Julian date argument added.

PNSW – name changed to TERCEL (TERrestrial-to-CELestial transformation). Input argument changed to UT1 Julian date in a pair of double-precision words.

CELPOL – input corrections to pole position can now be either (ΔX, ΔY) or ($\Delta\Delta\psi$, $\Delta\Delta\varepsilon$), the choice specified by a new input parameter. Units must now be in milliarcseconds.

SPIN – no longer specifically associated with sidereal time. Now applies a rotation about the current z-axis, with angle expressed in degrees.

SUNFLD – replaced by GRVDEF, a more general subroutine that evaluates the gravitational deflection of light due to several solar system bodies.

All of the high-level subroutines (PLACE, APSTAR, APPLAN, etc.) now assume that they are working with ICRS data; this goes for the input RA, Dec, and proper motion components for the star routines and the position and velocity vectors obtained from SOLSYS (e.g., from DE405) in both the star and planet routines. VPSTAR, LPSTAR, VPPLAN, LPPLAN, ASSTAR, ASPLAN, and MPSTAR produce output positions in the ICRS.

Significant Internal Changes to Code

Common error conditions will now generate error messages sent to unit=* (standard output, usually the terminal screen). Each error message always begins with the name of the subroutine that produced it, and is a plain-English description of the problem.

All subroutines that need astronomical constants now call ASTCON to obtain the values they need on their first call. Those values are SAVEd for use on subsequent calls. Those values are:

SPEED OF LIGHT IN METERS/SECOND — A DEFINING PHYSICAL CONSTANT:

$c = 299{,}792{,}458$

LIGHT-TIME FOR ONE ASTRONOMICAL UNIT IN TDB SECONDS, FROM DE405:

$a(\text{sec}) = 499.0047838061$

SPEED OF LIGHT IN AU/DAY:

$c(\text{AU/day}) = 86400 / a(\text{sec})$

LENGTH OF ASTRONOMICAL UNIT IN METERS:

$a = a(\text{sec}) \times c$

HELIOCENTRIC GRAVITATIONAL CONSTANT IN METERS^3/SECOND^2, FROM DE405:

$GS = 1.32712440017987 \times 10^{20}$

GEOCENTRIC GRAVITATIONAL CONSTANT IN METERS^3/SECOND^2, FROM DE405:

$GM = 3.98600433 \times 10^{14}$

EQUATORIAL RADIUS OF EARTH IN METERS, FROM IERS CONVENTIONS (2003):

$r_\oplus = 6,378,136.6$

FLATTENING FACTOR OF EARTH, FROM IERS CONVENTIONS (2003):

$f = 1 / 298.25642$

NOMINAL MEAN ROTATIONAL ANGULAR VELOCITY OF EARTH, IN RADIANS/SECOND, FROM IERS CONVENTIONS (2003):

$\omega = 7.2921150 \times 10^{-5}$

RECIPROCAL MASSES (SUN MASS/BODY MASS) FOR SOLAR SYSTEM BODIES

SUN = 1

MOON = 27,068,700.387534

MERCURY = 6,023,600

VENUS = 408,523.71

EARTH = 332,946.050895

MARS = 3,098,708

JUPITER = 1,047.3486

SATURN = 3,497.898

URANUS = 22,902.98

NEPTUNE = 19,412.24

PLUTO = 135,200,000

EARTH-MOON BARYCENTER = 328,900.561400

DE405 values are used for many of these, which are in TDB (T_{eph}) units. NOVAS output is practically insensitive to changes in low-order digits of the above constants; they are mostly used for relatively small corrections, such as the gravitational deflection of light. Probably the light-time for 1 AU is the most important, because it is used for the light-time correction. The constants that really matter in NOVAS are the coefficients to the series expansions in the individual subroutines, i.e., the constants that are embedded in the models for precession, nutation, etc.

APSTAR, TPSTAR, APPLAN, TPPLAN, VPSTAR, LPSTAR, VPPLAN, LPPLAN, ASSTAR, ASPLAN – now are simply "front-ends" to specific calls to PLACE. All substantive apparent place calculations of various kinds are now done only in PLACE. The following changes in the basic algorithms were made:

(1) Calls to FRAME were added in appropriate places to transform between the ICRS and the dynamical system.

(2) In updating a star's position for proper motion, there is now a correction to the epoch of interest for the difference in light-time between the solar system barycenter (the reference point for the input catalog data) and the Earth itself. (This affects only stars with the greatest proper motions, and then only at the 0.1 mas level). Uses the new subroutine DLIGHT to compute the epoch offset.

(3) The "Doppler factor", k, is included in the computation of stars' space motion vectors (see note on VECTRS).

(4) Modifications were made related to the change in gravitational deflection algorithms from SUNFLD to the more-general GRVDEF (see note on GRVDEF).

(5) Code has been introduced that allows a place to be expressed in the Celestial Intermediate Reference System (equator of date with CIO as right ascension origin).

(6) Code has been added that allows the input of an observer's instantaneous geocentric position and velocity vectors (with respect to the true equator and equinox of date) for a topocentric place calculation; this is included to support satellite observations.

TERCEL, SOLSYS – calls to FRAME added at appropriate places. (In SOLSYS, the call to FRAME is commented out for DE405 and later JPL ephemerides, since DE405 is in ICRS.)

CATRAN, GETHIP, VECTRS – code adjusted for new proper motion and parallax units.

CATRAN – code added to call FRAME for new IT=4 and IT=5 options that rotate data between dynamical J2000.0 system and ICRS.

VECTRS, CATRAN – 1/(sin(parallax)) now used to compute distance rather than 1/parallax; an inconsequential change, just to make the expression formally correct. Also, the "Doppler Factor", k, mentioned in the Hipparcos documentation and other papers, is now applied in computing the space-motion vector. The change in the units of proper motion and parallax is also implemented here.

SIDTIM – returns value of sidereal time, either mean or apparent. Internally can work by either of two methods, set by previous call to SETMOD, EQINOX, or CIOTIO:

Equinox-based method: Evaluates expression for mean sidereal time given in Capitaine et al. (2003), eq. (42). The Earth rotation angle θ is obtained from EROT. For apparent sidereal time, the equation of the equinoxes, including the "complementary terms", is obtained from ETILT.

CIO-based method: Obtains sidereal time from eq. (6) given in Kaplan (2003) in *IAU XXV, Joint Discussion 16: The International Celestial Reference System, Maintenance and Future Realizations*, p. 196. That equation is based on the position of the true equinox of date in the Celestial Intermediate Reference System, the basis of which is obtained from CIOBAS. The Earth rotation angle θ is obtained from EROT. Mean sidereal time, when requested, is obtained by *subtracting* the equation of the equinoxes, obtained from ETILT.

In either method, SIDTIM/EROT evaluates θ using the input UT1 epoch, but other components of sidereal time are evaluated using TDB (set equal to TT), with $TT=UT1+\Delta T$. Default value is $\Delta T=64$ sec, applicable at or near 2000; for highest precision applications, ΔT value can be set via prior call to SETDT.

TERCEL – performs the terrestrial-to-celestial transformation on a given vector, i.e., the total rotation from the ITRS to the ICRS. Internally can work by either of two methods, set by previous call to SETMOD, EQINOX, or CIOTIO:

Equinox-based method: Evaluates the old-style transformation as per previous subroutine PNSW, but with a call to FRAME added at the end to put final vector in ICRS. Uses apparent sidereal time, obtained from SIDTIM.

CIO-based method: Performs the transformation of eq. (4) given in Kaplan (2003), based on the Celestial Intermediate Reference System. The orthonormal basis of the system is obtained from CIOBAS and the Earth rotation angle θ is obtained from EROT.

In either method, the "fast angle" (rotation about z axis) is evaluated using the input UT1 epoch, but other components of the transformation are evaluated using TDB (set equal to TT), with $TT=UT1+\Delta T$. Default value is $\Delta T=64$ sec, applicable at or near 2000; for highest precision applications, ΔT value can be set via prior call to SETDT.

ETILT – now evaluates a more complete series for the complementary terms in the equation of the equinoxes (formerly just the two largest terms). Internally works in either high- or low-accuracy mode, set by previous call to SETMOD, HIACC, or LOACC:

High-accuracy mode: Obtains the sum of the terms from IERS function EECT2000.

Low-accuracy mode: Obtains the sum of the terms from a 9-term internal series.

ETILT uses the expression for the mean obliquity from the P03 precession formulation.

PRECES – now evaluates precession-angle polynomials for the Capitaine, et. al (2003) P03 model, the model recommended by an IAU resolution in 2006. Some code changes made to ensure reversibility of transformation (to/from J2000.0).

NOD – now just calls either of the nutation subroutines, NU2000A (from the IERS) or NU2000K (a reduced-accuracy version of NU2000A), to do the hard work; does not contain nutation series itself. Which of the two nutation subroutines is called depends on whether high-accuracy or low-accuracy mode has been chosen for Earth rotation calculations (see new subroutines SETMOD, LOACC, HIACC).

FUNARG – now evaluates expressions for the fundamental solar and lunar arguments from Simon et al. (1994), A&A 282, 663. However, IERS subroutine NU2000A, that evaluates the full nutation series, develops its fundamental arguments internally (a mixed bag of expressions).

WOBBLE – very tiny (inconsequential for most applications) rotation about z axis added to matrix to correct ITRS longitude origin to TIO, using recently published approximation to TIO longitude as a function of time (which required the new time argument added to this subroutine). Essentially, this changes W rotation to W'. Also changed matrix element expressions from first-order approximations to exact expressions for increased precision.

SOLSYS – the call to the JPL ephemeris-access routine has been changed from the single-argument JD call to the double-argument JD call; that is, from PLEPH to DPLEPH. The way SOLSYS now works is that if you give it a full JD, it just splits the integer part from the fractional part and sends these to DPLEPH separately. In this case the result is the same as a call to PLEPH with the JD in one piece. But, there is now a little bit of code so that if in a subsequent call to SOLSYS, the JD is between −1 and +1, SOLSYS will interpret it as a *fraction of a day* to be used with the *integral part of the JD from the previous call*. This way there is no effect on existing applications that directly use SOLSYS, but it provides a higher-precision option if two calls in succession are used in this way. The way to test whether SOLSYS can use split JDs is to check on whether the value of IDSS('JD') is 1 or 2, with 2 meaning that Julian dates can be split between successive calls.

<u>Other Internal Code Changes</u>

Many minor changes have been made in the code. Obviously many of the comment statements had to be revised, and others added, too numerous to try to list. Some of the code is now more Fortran-77-like and less Fortran-66-like, especially in the subroutines in which other changes had to be made; a uniform scrub was not done. NOVAS still has plenty of ancient-looking code, it's still all-caps, and there are still some GO TOs. On the other hand, since NOVAS is mostly computational, flowing top-to-bottom within each subroutine, without any complicated logic, it hardly matters.

Some variable names were changed. For example, the variable PI in some subroutines was used for the parallax and not the mathematical constant π=3.14159…, which could be confusing. In these cases, the parallax variable name is now PX. The input (catalog) RA and Dec for many subroutines had been named RAM and DECM, the M indicating "mean"; these are now RAI and DECI, the I indicating "ICRS". Many similar trivial changes have been made.